GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G45842.1

Manuscript received 13 August 2018
Revised manuscript received 28 November 2018
Manuscript accepted 30 November 2018

Published online 4 January 2019

Southern Hemisphere sea-surface temperatures during the Cenomanian–Turonian: Implications for the termination of Oceanic Anoxic Event 2

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ABSTRACT

Mesozoic oceanic anoxic events (OAEs) were major perturbations of the Earth system, associated with high CO_2 concentrations in the oceans and atmosphere, high temperatures, and widespread organic-carbon burial. Models for explaining OAEs and other similar phenomena in Earth history make specific predictions about the role and pattern of temperature change, which can be tested through comparison with the geological record. Oceanic Anoxic Event 2 (OAE 2) occurred ~94 m.y. ago and is commonly considered as the type example of an OAE. However, temperature change during this event is constrained largely from Northern Hemisphere sites. In order to understand whether such records represent global patterns, we use an organic geochemical paleothermometer (TEX_{86}) to provide the first detailed Cenomanian–Turonian record of paleotemperatures from the Southern Hemisphere (Ocean Drilling Program Site 1138; paleolatitude of ~47°S). Consideration of this record, Northern Hemisphere records, and general circulation model simulations suggests that global temperatures peaked during OAE 2 but remained high into the early Turonian due to elevated CO_2. These results suggest that the burial of organic carbon during the whole of OAE 2 did not, of itself, lead to global cooling and that CO_2 remained high into the early Turonian. This climatic evolution suggests that cooling was not the driving mechanism for the termination of OAE 2 and that cessation of widespread anoxic conditions required changes in other factors, such as sea levels, the availability of easily weathered silicate rocks, and/or nutrient sequestration in black shales.

INTRODUCTION

Oceanic anoxic events (OAEs) were brief intervals of Mesozoic time characterized by increased accumulation rates of marine organic carbon in globally distributed basins, associated with major perturbations of seawater chemistry and climate (Schlanger and Jenkyns, 1976; Jenkyns, 2010). Oceanic Anoxic Event 2 (OAE 2) in the late Cenomanian was likely triggered by large-igneous-province volcanism (Turgeon and Creaser, 2008; Du Vivier et al., 2014; Holmden et al., 2016), which released CO_2, and possibly biolimiting nutrients, into the ocean and atmosphere (see Jenkyns et al., 2017). Various proxies lend support to a canonical model that suggests that increased CO_2 led to a greenhouse climate, characterized by higher temperatures, increased wind-driven upwelling, an invigorated hydrological cycle, and enhanced weathering rates of silicate rocks, which, in turn, raised the supply of nutrients to the surface ocean and caused local salinity stratification (e.g., Arthur et al., 1988; Jenkyns, 2010; Robinson et al., 2017). These climatic and oceanographic factors would have promoted the production and preservation of organic carbon in a range of marine depositional settings. This model suggests that burial of organic carbon should have reversed greenhouse conditions and led to global cooling (e.g., Arthur et al., 1988). There is some evidence for the operation of this mechanism during OAE 2 in the form of an interval of widespread cooling in the Northern Hemisphere, known as the Plenus Cold Event (PCE), recognized initially by the southward movement of a boreal belemnite, *Praeactinocamax plenus,* and an associated cool-water fauna (Gale and Christensen, 1996; Jenkyns et al., 2017).

Notwithstanding the PCE, existing temperature reconstructions (all from the Northern Hemisphere) suggest that temperatures remained high throughout OAE 2 and into the early Turonian (Jenkyns et al., 1994; Voigt et al., 2004; Forster et al., 2007; Sinninghe Damsté et al., 2010; van Helmond et al., 2014; O'Brien et al., 2017). The proxy evidence for relatively high and constant temperatures from the latter stages of OAE 2 and the immediate post-event phase seemingly contradicts the theory that increased organic-carbon burial led to a reversal of greenhouse climatic conditions and a subsequent return to normal, generally oxic, marine conditions (Jenkyns, 2010; Robinson, et al., 2017).

Whether the protracted period of warmth extending into the early Turonian was restricted to the Northern Hemisphere or was a global phenomenon is unclear, as existing climate reconstructions all derive from the circum–North Atlantic region and may be biased by changes in regional climate or ocean circulation. To address the issue of regional versus global temperature trends, the first high-resolution record of paleotemperatures from the Southern Hemisphere across the OAE 2 interval is presented here from Ocean Drilling Program (ODP) Site 1138 on the Kerguelen Plateau, presently located in the southern Indian Ocean. Paleotemperatures are reconstructed using TEX_{86} (Schouten et al., 2013), an organic paleothermometer, which exploits the empirical relationship between temperature and the relative abundance of isoprenoid glycerol dialkyl glycerol tetraethers (isoGDGTs). These molecules are membrane lipids produced by archaea that have varying

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CITATION: Robinson, S.A., et al., 2019, Southern Hemisphere sea-surface temperatures during the Cenomanian–Turonian: Implications for the termination of Oceanic Anoxic Event 2: Geology, v. 47, p. 131–134, https://doi.org/10.1130/G45842.1.

numbers of cyclopentane rings and, in the case of crenarchaeol and its regioisomer, a cyclohexane ring. Culture and field studies show that with increasing temperature, the relative abundance of isoGDGTs containing higher numbers of cyclopentane rings increases, as does the relative abundance of the regioisomer of crenarchaeol. These changes in isoGDGT distributions can be quantified in a sample by the TEX_{86} ratio (Schouten et al., 2013).

MATERIALS AND METHODS

ODP Site 1138 was drilled on the Kerguelen Plateau (Fig. 1; present-day location: 54°S, 076°E), a large igneous province that formed during the Early Cretaceous. Subsequently, during the Cenomanian, the Kerguelen Plateau subsided below sea level and marine sediments accumulated in neritic environments, which transitioned to bathyal pelagic environments during the Turonian (Holbourn and Kuhnt, 2002). An organic carbon–rich interval (total organic carbon up to 15%) occurring in Core 69R from Site 1138 has been dated as Late Cenomanian and represents the local record of OAE 2 (Dickson et al., 2017). Detailed bio- and chemostratigraphy indicate that sediments deposited during the earliest phase of OAE 2 are missing due to a hiatus, but that a relatively continuous record exists of the remainder of the event (Dickson et al., 2017). Methods for biomarker extraction and measurement of GDGTs (both isoGDGTs and branched GDGTs) are described in the GSA Data Repository[1].

RESULTS

TEX_{86} values in Core 69R range from 0.70 to 0.91 and show a distinct stratigraphic pattern (Fig. 2) characterized by four intervals (A–D). In interval A (658.29–656.94 m corrected depth [mcd]), TEX_{86} values are variable, with an average of 0.76 ($1\sigma = 0.04$, $n = 19$). In interval B (656.94–656.24 mcd), immediately above the hiatus at the base of the OAE 2 level, TEX_{86} values increase from 0.84 to 0.91 (average 0.88; $1\sigma = 0.02$, $n = 8$). In interval C, TEX_{86} values remain relatively constant with little variability around an average of 0.90 ($1\sigma = 0.01$, $n = 8$). From ~655 mcd to the top of Core 69R, TEX_{86} values gradually decrease to ~0.84 (interval D; average 0.87; $1\sigma = 0.03$, $n = 37$). In order to assess the origins of the isoGDGTs, other GDGT-based indices (e.g., branched and isoprenoid tetraether [BIT] index, methane index, relative abundance of GDGT-0 [%GDGT-0], ring index [|ΔRI|]) were calculated, and the values are provided in the Data Repository.

DISCUSSION

Evaluation of the TEX_{86} Values

The input of soil-derived branched GDGTs, *in situ* GDGT production, or archaeal populations that deviate from the "normal" modern marine calibration can all lead to TEX_{86} values that are not representative of paleotemperatures and can be can be assessed via indices such as BIT, methane index, %GDGT-0, or |ΔRI| (Schouten et al., 2013; O'Brien et al., 2017). For Site 1138, the values of these indices are consistent with deposition in normal marine conditions and do not suggest anything atypical about the overall composition of the isoGDGTs (see the Data Repository). Following deposition, burial diagenesis can alter TEX_{86} values (Schouten et al. 2004), but the C_{31} homohopane $\beta\beta / (\beta\beta + \beta\alpha + \alpha\beta)$ (a biomarker proxy for thermal maturity) values from Site 1138 are generally >0.5 suggesting that the organic matter in Core 69R is thermally immature (Dickson et al., 2017) and suitable for TEX_{86} paleothermometry.

Southern Hemisphere Paleotemperature Trends during OAE 2

In depth interval A, TEX_{86} values are relatively variable, possibly due to unrecognized hiatuses and/or fluctuating environmental conditions associated with subsidence during the late Cenomanian (Dickson et al., 2017). Above the hiatus at the base of the OAE 2 level in interval B, TEX_{86} values increase, suggesting a period of warming during the event. This depth interval lies between the highest occurrence of the nannofossil *Axopodorhabdus albianus* and that of *Microstaurus chiastius* and is equivalent

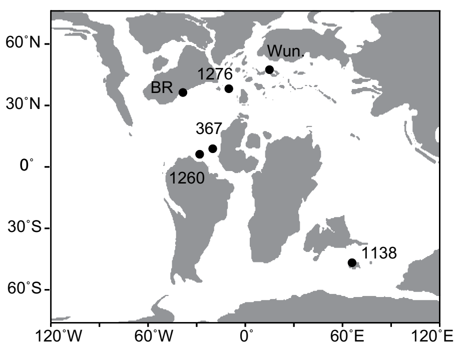

Figure 1. Paleogeographic reconstruction for Turonian showing position of sites discussed in the text. BR—Bass River; Wun.—Wunstorf. Site numbers are Deep Sea Drilling Project site (367) and Ocean Drilling Program sites (1138, 1260, 1276).

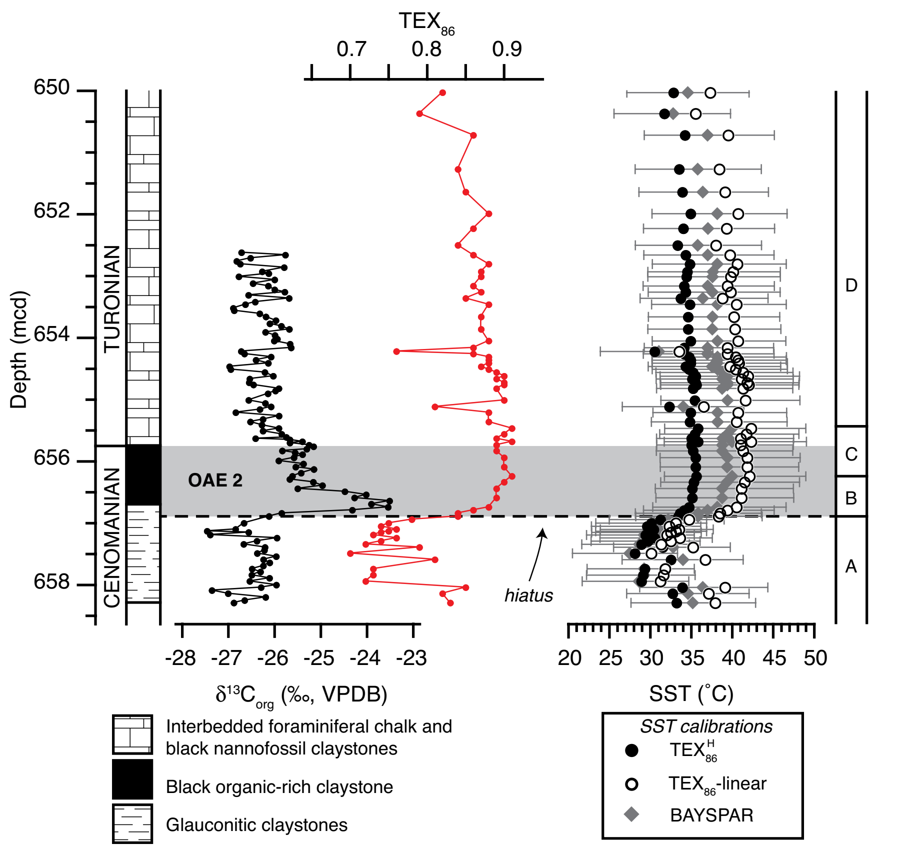

Figure 2. Carbon-isotope stratigraphy (Dickson et al., 2017), TEX_{86} data, calculated sea-surface temperatures (SSTs), and depth intervals (A–D; described in text) from Ocean Drilling Program Site 1138, Core 69R. SSTs calculated using the following empirical calibrations: TEX-linear (O'Brien et al., 2017); TEX_{86}^{H} (Kim et al., 2010); and the deep-time version of BAYSPAR (Tierney and Tingley, 2015). Error bars for BAYSPAR values show 5th to 95th percentiles. OAE 2—Oceanic Anoxic Event 2; mcd—m corrected depth; VPDB—Vienna Peedee belemnite.

[1]GSA Data Repository item 2019052, containing methods, supplementary figures, and GDGT data, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

to an interval of warming following the PCE (Dickson et al., 2017; Jenkyns et al., 2017). This pattern suggests that interval B at Site 1138 represents a partial record of the recovery from the PCE and, if this is correct, indicates that the PCE was indeed a global phenomenon, likely driven primarily by the concomitant lowering of atmospheric CO_2 (e.g., Jarvis et al., 2011; Jenkyns et al., 2017) and not just a local response to changing surface-water circulation patterns in the Northern Hemisphere. Interval C spans the latter stages and termination of OAE 2. Peak temperatures were reached during this interval and remained relatively high during the termination of OAE 2 into the early Turonian, before showing a slight decline in interval D. Two samples within interval D have significantly lower TEX_{86} values, although neither sample is associated with anomalous values in any other indices.

TEX_{86} has been previously calibrated to sea-surface temperatures (SSTs) using a number of approaches and is the subject of much ongoing debate (Schouten et al., 2013; O'Brien et al., 2017). Applying commonly used SST calibrations to the Site 1138 data suggests maximum SSTs during OAE 2 >36 °C and an increase in average SSTs of ~4–8 °C (dependent on calibration) from pre–OAE 2 times (interval A) to the peak of OAE 2 (interval C). Equally high TEX_{86} values (>0.9) have been reported during the peak of OAE 2 in the Northern Hemisphere, from equatorial to mid-latitudes (Forster et al., 2007; Sinninghe Damsté et al., 2010; van Helmond et al., 2014, 2015; Fig. DR1 in the Data Repository). The commonality in TEX_{86} values suggests that the remarkably flat meridional temperature gradient noted for the Northern Hemisphere during OAE 2 (Sinninghe Damsté et al., 2010) was present in both hemispheres, at least as far south as Site 1138. The 2–3 °C warming (dependent on calibration) in interval B at Site 1138 is consistent with Northern Hemisphere $\delta^{18}O$ and TEX_{86} reconstructions of the SST warming that occurred at the end of the PCE (e.g., Forster et al., 2007; Jarvis et al., 2011; van Helmond et al., 2014, 2015).

Significance for Understanding OAE 2

The pattern of long-term temperature variability during OAE 2 at Site 1138 is very similar to that of other records from the Northern Hemisphere that also indicate sustained warmth during and after OAE 2 without returning to pre–OAE 2 values (e.g., Voigt et al., 2004; Forster et al., 2007; Sinninghe Damsté et al., 2010; van Helmond et al., 2014, 2015; Fig. DR1). This observation contradicts the canonical model (e.g., Jenkyns, 2010; Robinson et al., 2017), which suggests that following an initial, transient increase in CO_2-driven warming, burial of organic carbon would have lowered atmospheric pCO_2 and reversed greenhouse warming, leading to the cessation of conditions conducive to organic-carbon burial. The high temperatures in the early Turonian must therefore either indicate a long-term change in surface-water circulation patterns, leading to enhanced warmth in the early Turonian at the studied locations, or an excess of CO_2 supply (likely from volcanism) that was not sequestered by organic-carbon burial and silicate weathering during OAE 2. Changing circulation has previously been invoked to explain circum–North Atlantic warming after the PCE (e.g., Voigt et al., 2004). General circulation model (GCM) simulations of Cenomanian and Turonian climate at constant CO_2 levels (of 2× and 4× pre-industrial; Lunt et al., 2016; see the Data Repository) suggest that the effect of paleogeographic change on SSTs into the Turonian was small (0.31 °C at 2× CO_2; or 0.55 °C at 4× CO_2). This pattern is also true at key sites, where the effect of changing paleogeography on SSTs without any CO_2 change is between −0.6 and +1.8 °C (Fig. 3; Figs. DR2 and DR3). These simulations indicate that, in the absence of increasing pCO_2, significant global warming would likely not have occurred between the Cenomanian and Turonian due to paleogeographic change alone. Using the same GCM simulations, it is possible to consider the effect of doubling pCO_2 levels, with and without changes in paleogeography (Fig. 3; Figs. DR4–DR6). This analysis suggests ~3–4° of global warming into the Turonian and warming at all key sites in the range of 1.3–5.7 °C. The range of predicted warming from the Cenomanian to the Turonian at key sites is comparable to estimates calculated from proxies (Fig. 3). Assuming a linear response between CO_2 and temperature, these model–data comparisons indicate that the warming may have been driven by an approximate doubling of CO_2 concentrations, although a model with a higher (lower) climate sensitivity than the one used here would result in smaller (larger) inferred change in absolute CO_2.

Records of relative pCO_2 change that span OAE 2, including the termination phase in the early Turonian, suggest that minimum pCO_2 values were attained around the PCE and that concentrations of this greenhouse gas were relatively high during the termination of OAE 2 and the early Turonian (Jarvis et al., 2011; Gale et al., 2018), consistent with the overall trends in temperature determined by TEX_{86} and oxygen isotopes. In attempting to explain the observation of early Turonian warmth, Forster et al. (2007) suggested that organic-carbon burial was insufficient to counterbalance an increase in atmospheric CO_2 during the latter stages of OAE 2. However, this does not explain why organic-carbon burial rates declined while CO_2 remained high or was rising, which would, presumably, have led to a greenhouse climate that would have promoted increased organic-carbon burial through, for example, wind-driven upwelling, an enhanced hydrological cycle, or local basin stratification. This conjecture is supported by proxy evidence from the New Jersey margin (northeastern USA) that suggests an enhanced terrestrial hydrological cycle during most of OAE 2 (except during the PCE) and the early Turonian (van Helmond et al., 2014). Yet carbon-isotope and lithological records of OAE 2 clearly show that the factors controlling organic-matter burial waned in order for the event to terminate and that alternative explanations are required to reconcile the proxy records of climatic evolution. Sea-level rise during the latter half of OAE 2 may have reduced rates of weathering, erosion, and nutrient supply to the open ocean (Jarvis et al., 2011).

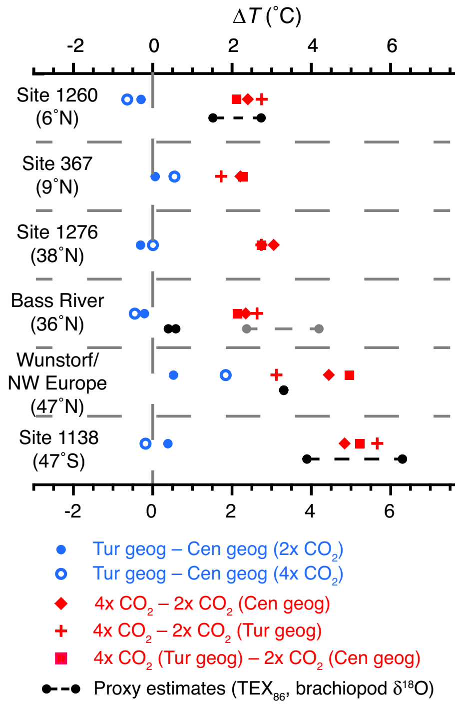

Figure 3. Estimates of the difference in temperature (Δ*T*) at grid-point localities of Oceanic Anoxic Event 2 (OAE 2) sites (see Fig. 1) between the Turonian and Cenomanian based on general circulation model simulations. In blue are shown Δ*T* values between Turonian and Cenomanian simulations assuming no CO_2 change and only geographic change (Tur geog – Cen geog; in blue); in these simulations, CO_2 levels were kept constant at either 2× or 4× pre-industrial values (2× CO_2, 4× CO_2). In red are shown Δ*T* values between simulations at 4× and 2× pre-industrial CO_2 levels assuming either constant geography (Cen geog or Tur geog) or a combination of both CO_2 and geographic change [4× CO_2 (Tur geog) – 2× CO_2 (Cen geog)]. In black are shown proxy estimates of Δ*T* between early Turonian and Cenomanian temperatures at localities for which sufficient data are available (data from this study, Forster et al. [2007], and Voigt et al. [2004]; see the Data Repository [see footnote 1]). For Bass River (Fig. 1), proxy estimates in black are based upon average Cenomanian temperatures; in gray, the minimum Cenomanian temperature has been used (see the Data Repository for discussion). Paleolatitudes are based on paleogeographies used in Lunt et al. (2016). Site numbers are from Deep Sea Drilling Project (367) or Ocean Drilling Program (1138, 1260, 1276).

Alternatively, or additionally, the exhaustion of easily weathered materials (e.g., freshly erupted submarine or subaerial basalts) may have led to a reduction in silicate weathering rates and nutrient supply, leading to reduced CO_2 sequestration. Continental weathering appears to have been most intense in an initial pulse during OAE 2 (Blättler et al., 2011; Pogge von Strandmann et al., 2013), while contributions to seawater of osmium and chromium from basaltic weathering appear to have declined before the end of OAE 2 (Du Vivier et al., 2014; Holmden et al., 2016). Furthermore, prior to OAE 2, warm climates and low rates of tectonic supply of fresh silicate rocks during the mid-Cretaceous may have reduced the weatherability of continental rocks and the effectiveness of silicate weathering to sequester additional CO_2 supplied during OAE 2 (as suggested for the Middle Eocene Climatic Optimum; van der Ploeg et al., 2018). Finally, the availability of key nutrients was also likely significant in determining how much CO_2 could be removed from the ocean-atmosphere reservoir, and there is abundant evidence for the global sequestration in black shales of key metal nutrients during OAE 2 that could have led to changes in the abundance of major phytoplankton groups (e.g., Jenkyns, 2010; Owens et al., 2016; Dickson et al., 2017; Jenkyns et al., 2017).

In summary, a combination of sea-level rise, a reduced efficiency of silicate weathering, and perturbed nutrient cycles in the latter part of OAE 2 may have led to a reduction in organic-carbon burial rates. As less carbon was being sequestered, atmospheric CO_2 was able to remain high and maintain global warmth into the early Turonian. These factors that affected the relationship between carbon cycling, climate, and the termination of OAEs are not readily captured by the canonical model and provide further evidence that simple environmental reconstructions cannot be used universally to explain all features of all similar events in Earth history (e.g., Robinson et al., 2017; van der Ploeg et al., 2018).

ACKNOWLEDGMENTS

We thank the Natural Environment Research Council (UK) for funding (NE/K012479/1, NE/K014757/1) and the International Ocean Discovery Program for access to samples. Getech Plc is acknowledged for providing paleogeographies used in Lunt et al. (2016). We acknowledge the helpful comments of the anonymous reviewers and editor Judith Totman Parrish.

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